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článek č. 1

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INFLUENCE OF THE INITIAL IMPERFECTIONS WITH REGARD TO THE WEBS THICKNESSES OF COLD-FORMED COMPRESSED STEEL MEMBERS

Abstract

Local stability requirements related to unfavorable buckling effects of compressed parts of cold-formed profiles are highly significant. Favorable effects related to their post-critical behavior are also important. The paper deals with resistance of these type of members, taking into account the influence of initial imperfections with regard to the thicknesses of their webs. The paper also presents information about experimental and theoretical-numerical research to determine the resistance of cold-formed compressed steel members with closed cross-sections. Obtained results are very extensive; therefore the paper presents results of part of tested and analyzed member.

Keywords

Cold-formed, initial imperfections, post-critical behavior, 3D modeling.

1 INTRODUCTION

The implementation of European standards into the national normative systems of European countries is connected with new methods and procedures for the calculation of cold-formed profiles and members [1 and 2]. This fact led to further investigation using theoretical- numerical analysis accompanied by experimental research. The research, mentioned in this paper, is a continuation of previous research project [3].

The experimental program included cold-formed testing members with square and rectangular cross-sections. Theoretical and numerical analysis has been oriented towards the investigation and modeling of initial imperfection effects, taking into account the influence of the thicknesses of their webs, while the experimental investigation has been realized to investigate the real behavior of these members during the loading process and to verify the obtained theoretical results. Presented results in this paper are chosen for members with rectangular cross-sections, see Figure 1.

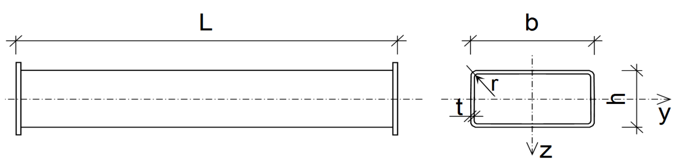

Fig. 1: Members with rectangular cross-sections

The members' lengths were designed to eliminate the global stability problems, in order to decide of the members' cross-sectional resistance. On the other hand, different dimensions of designed cross-sections were selected to reflect the post-critical behavior of individual thin webs

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during loading processes. In general, the webs of individual members are thin-walled at the compressive strain [4, 5, 6 and 7]. he tested members were made from steel sheets with nominal thickness 2 mm.

The numerical analysis was based on the modelling of actually measured initial imperfections as spatial areas, also on 3D simulations of the experimental tests with non-linear calculation procedures using software ANSYS based on the FEM, [8 and 9]. In the beginning, 3D models of tested members have been created for the comparison with experimental results and to verify the accuracy of numerical simulations. In the next step, 3D models of the same members with thicknesses 3 and 4 mm were created to reflect the impact of initial imperfections with regard to the thicknesses of their webs, see Table 1 and 2.

Tab. 1: Designed dimensions for testing and analysis

Members		Geometrical dimensions [mm]				
Cross-sectional group	Marking	b	h	t	r	L
B2	B21, B22, B23	200	100	2	3	650
B3	B31, B32, B33	200	100	3	3	650
B4	B41, B42, B43	200	100	4	3	650

Tab. 2: Dimensions and material properties of real members

Members	b	h	t	r	L	f_y	f_u
	[mm]					[MPa]	
B21, B31, B41	207.47	103.18	2, 3, 4	3	650.00	242.33	360
B22, B32, B42	207.93	103.08	2, 3, 4	3	649.88	242.33	360
B23, B33, B43	207.35	102.62	2, 3, 4	3	649.25	242.33	360

2 EXPERIMENTAL TESTING METHODOLOGY AND RESULTS

Before testing start, the initial imperfections (initial buckling shapes) of all webs of tested members were measured on previously generated raster [5 and 7]. During consecutive programmed loading of the tested members, the strains ε were measured using resistive strain-gauges located in their middle cross-sections. Deflections (buckling) of the webs w were measured using inductive sensors located in different places according to members lengths. Figure 2 illustrates the concept of the generated raster and arrangement of the test.

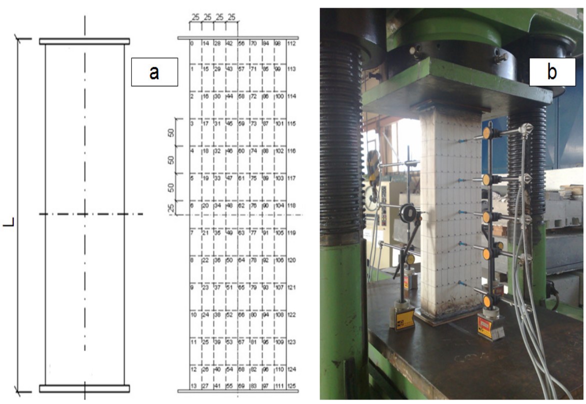

Fig. 2: Generated raster (a) and arrangement of the test (b)

The resistive strain-gauges and inductive sensors were connected to the computer for direct evaluation of obtained results. Loading process of each member was regulated according to its real behavior, measured strains ε and deflections w. Each test continued until total failure of tested members, defined by the beginning of continuous increasing strains ε and deflections of the webs w. The final buckling shapes after test finishing were also revealed. Example of the test completion and overall failure of tested member B22 is given by Figure 3.

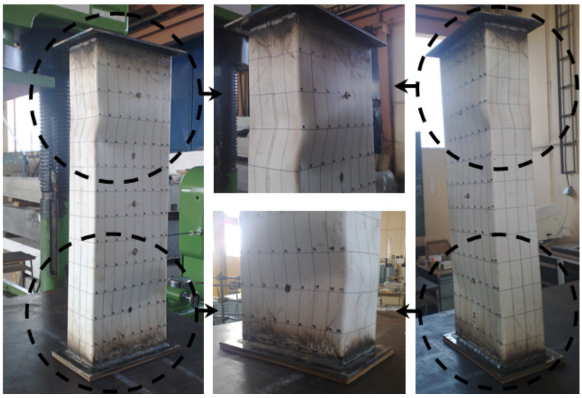

Fig. 3: Test completion and overall failure - member B22

Taking into account the real-measured dimensions and yield stresses, the resistances of all tested members were calculated according to relevant standards [1 and 2]. Theoretical resistances and experimental limit loads of cross-sectional group B2 are presented in Table 3.

Tab. 3: Theoretical and experimental limit loads

Member	$N_{c,RK}$	$N_{b,Rky}$	$N_{b,Rkz}$	N_{exp}	Description of the individual limit loads	
	[kN]				$N_{c,RK}$	Resistance of the cross-section for compression
B21	194.45	194.45	194.45	171.15	$N_{b,Rky}$	Buckling resistance of the member for compression (in our case $N_{c,Rk} = N_{b,Rk}$)
B22	200.55	200.55	200.55	164.77	$N_{b,Rkz}$	
B23	191.76	191.76	191.76	173.27	N_{exp}	Measured experimental limit load

It is evident from Table 3 that the experimental limit loads are smaller than theoretical resistances calculated according to the relevant standards in the all cases. This serious fact could occur as a result of the unfavorable development of initial imperfections. This unfavorable influence of the initial imperfections is analyzed in detail in the following sections of this paper.

3 ANALYSIS OF THE INITIAL IMPERFECTIONS

The experimental limit loads were smaller than the expected theoretical values for all tested members. One of the possible reasons are the sizes and shapes of initial imperfections. In terms of tolerance values, maximal measured discrete value of the initial imperfection of the webs was 1.51 mm and the maximal tolerated imperfection is given in the standard as $b/50$, which is 4.15 mm [10]. It follows that the problem is not in the size of these imperfections but in their distribution and shape. The referred standard [10] permits maximal tolerated value $b/50$ for imperfections in sinusoidal waves form as shown in Figure 4.

The initial imperfections of all tested members were modeled in mathematical software MATLAB as spatial areas. The results showed that none of the webs had uniform initial imperfection shape, and not at all sinusoidal waves form. Figures 5 and 6 illustrate the shape of initial imperfections for the relevant webs of member B21. Midline initial imperfections of all webs are illustrated by graphs in Figure 7.

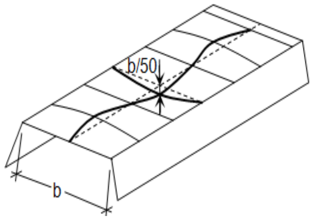

Fig. 4: Tolerated initial imperfections according to [10]

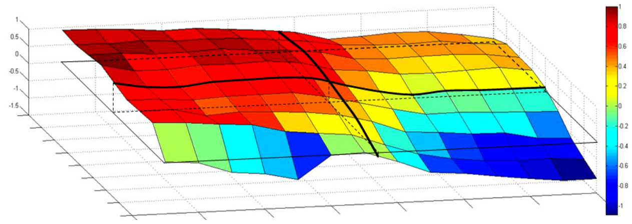

Fig. 5: Initial imperfections shape of member B21 - web 1

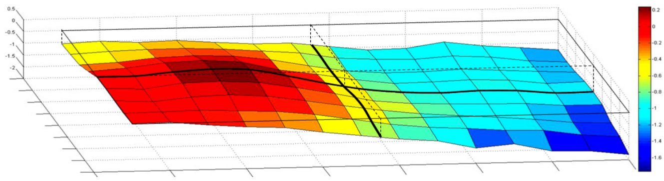

Fig. 6: Initial imperfections shape of member B21 - web 2

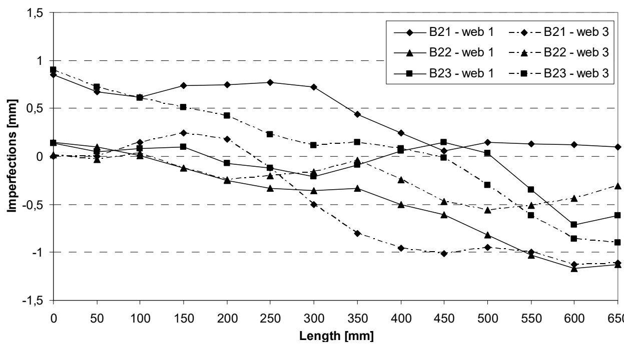

Fig. 7: Midline initial imperfections of all webs, cross-sectional group B2

The overall analysis of the initial imperfections shapes for all tested members indicates that the expected tolerated shape in the relevant standard [10] is theoretical and cannot be achieved realistically. However, the sinusoidal waves form is the most unfavorable and any other shape would be safer in terms of stability. The spatial areas in Figures 5 and 6, also the graphs in Figure 7, clearly declare that the initial imperfection is a random variable and must be more precisely reflected in the calculation procedure. For these reasons detailed theoretical and numerical analysis were performed using software based on the FEM – ANSYS.

4 CREATED MODELS AND EXPERIMENT SIMULATION

Volume shell finite element SOLSH190, quad and triangular, was used to create the calculation models. The finite element SOLSH190 is usually used for the simulation of shell structures with wide range of thicknesses. This kind may be used to solve the geometrical and physical nonlinear problems [11, 12 and 13]. This element with eight connecting nodes has three degrees of freedom at each node, see Figure 8.

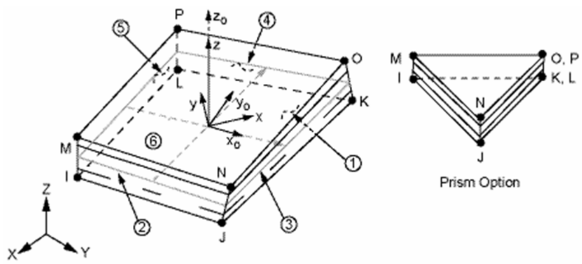

Fig. 8: Shell element SOLSH190 and integration points

Each of the 3D calculation models contains 4 182 nodes and 4 100 shell elements. Boundary conditions of the modeled, axially compressed, members were defined by two-sided hinged connections. Elastic-plastic material with hardening was considered. This material is characterized by a bilinear approximation of the strain-stress diagram of steel. The measured value of yield stress f_y = 242,33 *MPa* and the hardening modulus E_{hard} = 2800 MPa were considered. The plastic zones method was used here.

The concept of calculation model configuration and the mesh of volume shell finite elements SOLSH190 are presented in Figure 9.

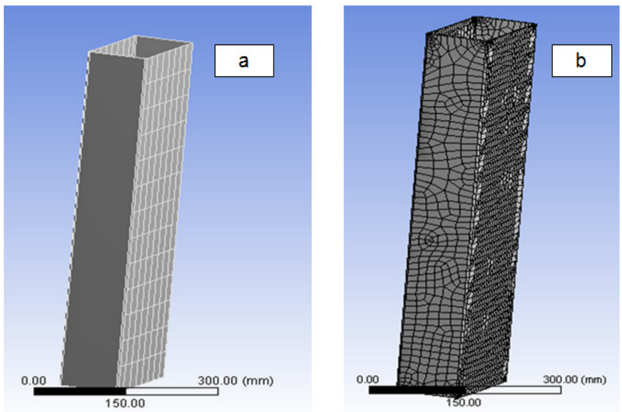

Fig. 9: Configuration of the calculation model (a) and volume shell finite elements mesh (b)

Two types of calculation models were used to verify the initial imperfections effect:
- Calculation models which consider the initial imperfections of the webs.
- Calculation models which do not consider the initial imperfections of the webs.

The applied load was transformed to the middle-plane of the shell elements with sequential loads increasing until the initial appearance of plastic zone (on the internal surface of the web). By the continuation of sequential load increasing, the development of plastic zone manifested over the external surface of the web. The sequential loading was monitored until the divergence of the calculation (collapse of the member).

Figure 10 illustrates the resistances obtained by calculation according to relevant standard, by numerical (FEM) simulations and by experimental investigation of tested members B21, B22 and B23.

Figure 10 indicates the conformity between theoretical calculation according to EN 1993-1-3:2006 and FEM simulation – without considering the initial imperfections. This figure also indicates the conformity between experimental results and FEM simulation – taking into account the initial imperfections. This fact proves the correctness of ideas and procedures in creating the calculation models, i.e. these calculation models can be used for further analysis and calculations. According to this detailed analysis, the same method were used to create models with different thicknesses.

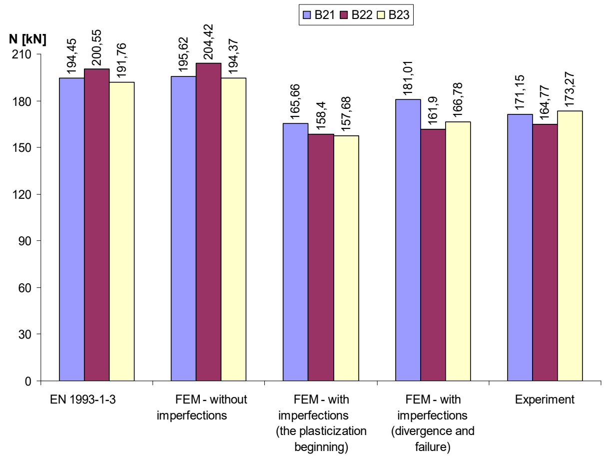

Fig. 10: Resistances of members B21, B22 and B23

5 RELATIONSHIP BETWEEN THE INITIAL IMPERFECTIONS AND THICKNESSES

In accordance with Table 2, members of webs thickness 2 mm were modeled with a thicknesses 3 mm and 4 mm. All other parameters including geometrical dimensions, initial imperfections and material properties were maintained. Obtained results are illustrated in the following figures.

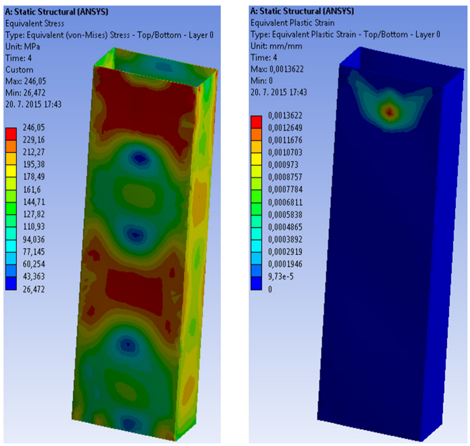

Fig. 11: Equivalent stress and equivalent plastic strain - member B22

In the case of members with webs thickness 2 mm, the overloading effected the redistribution of initial imperfections and the broadening of plastic zones over the surface in the upper part of the length. In the beginning, the maximal equivalent stress appeared in the same place and broadened at the down part under the middle of the length, see Figure 11.

In the case of members with thickness 3 mm, the redistribution of initial imperfections had different development. The broadening of plastic zones over the surface appeared in the down part of the length. The maximal equivalent stress appeared in the same place and broadened at the upper part above the middle of length, see Figure 12.

The situation in the case of members with thickness 4 mm is very similar to the case with the thickness 3 mm. The broadening of plastic zones also appeared in the down part of the length. The maximal equivalent stress has appeared on a smaller scale at the lower part of the member and broadened at the upper part above the middle of the length, see Figure 13.

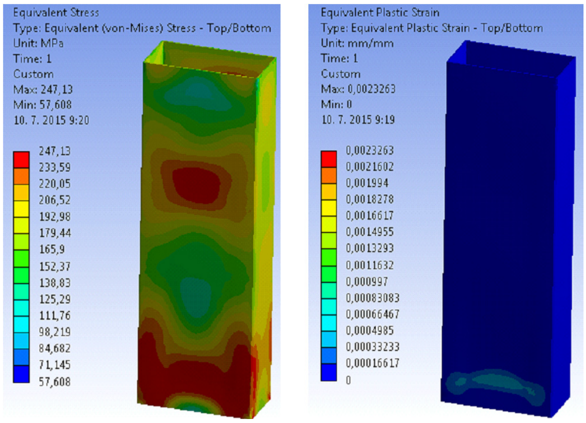

Fig. 12: Equivalent stress and equivalent plastic strain - member B32

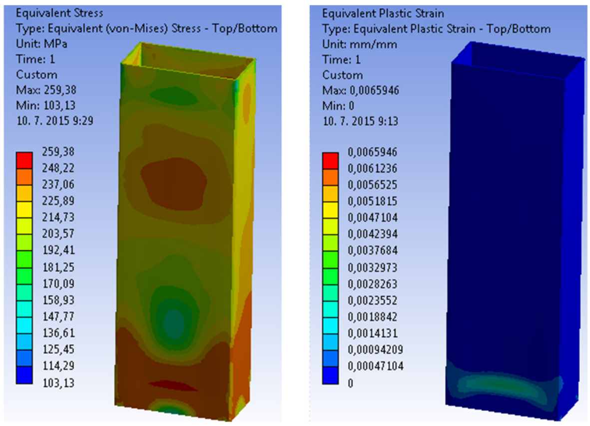

Fig. 13: Equivalent stress and equivalent plastic strain - member B42

6 RESULTS AND THEIR ANALYSIS

Following the above mentioned ideas and procedures, the resistances of all members with webs thicknesses 2 mm, 3 mm and 4 mm have been determined. For improved illustration of the resistances, obtained by the calculation according to relevant standard and by FEM numerical simulations, graphical representation of their values is given by Figures 14, 15, 16 and 17.

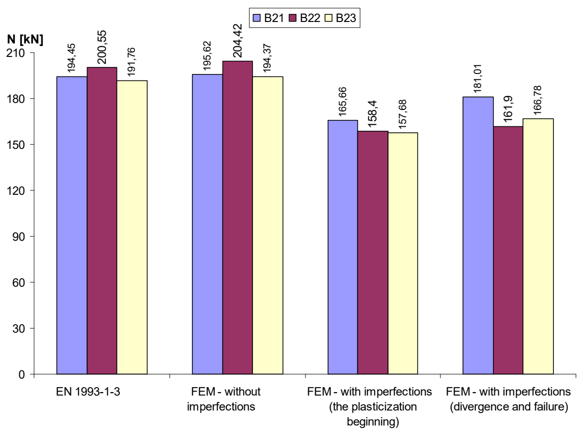

Fig. 14: Obtained results and resistances, members B21, B22 and B23

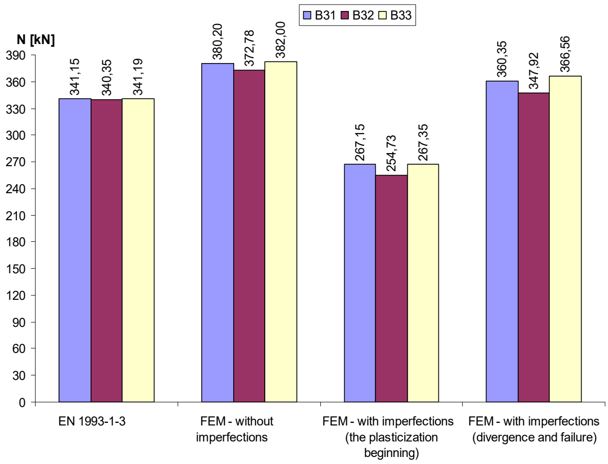

Fig. 15: Obtained results and resistances, members B31, B32 and B33

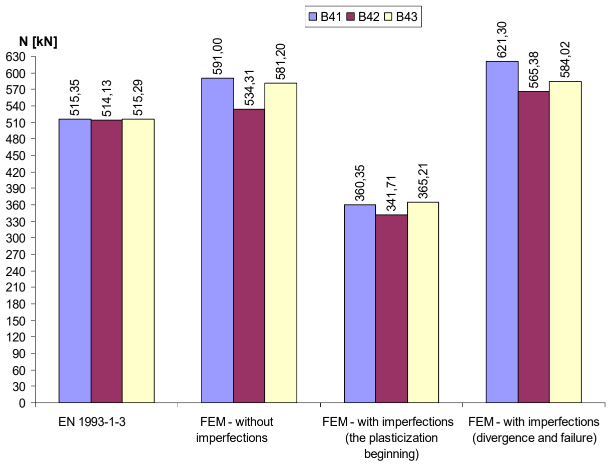

Fig. 16: Obtained results and resistances, members B41, B42 and B43

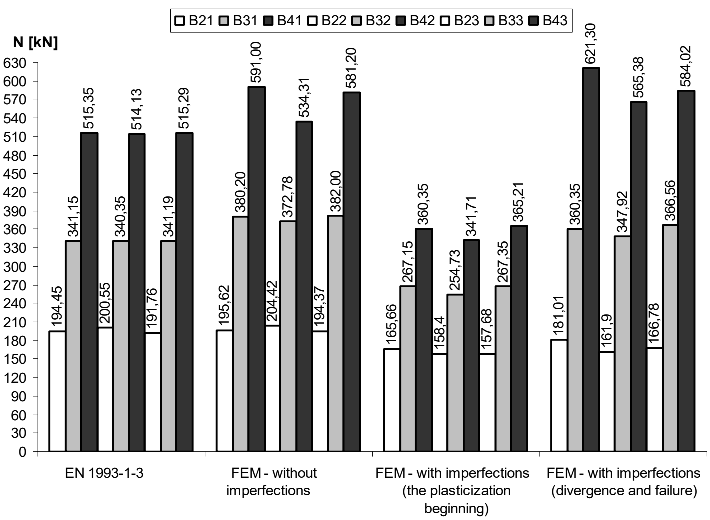

Fig. 17: Comparison of obtained results for all considered members

Figure 14 illustrates the results of cross-sectional group B2, i.e. members with 2 mm thick webs (see also Tab. 3 and Fig. 10). This figure indicates the serious influence of initial imperfections and suggests that the calculation according to relevant standard is not on the safe side. From this figure it is evident that the zone between plasticization beginning and failure is very small.

Figures 15 and 16 illustrate the results of cross-sectional groups B3 and B4, i.e. members with 3 mm and 4 mm thick webs. These figures indicate the receding of the initial imperfections effect and suggest that the calculation according to relevant standard is on the safe side. Figures 15 and 16 also indicate that the zones between plasticization beginning and failure are markedly bigger. The comparison of individual results for all considered members is given by Figure 17.

7 CONCLUSIONS

According to obtained experimental results, basing on data acquired from the calculation models and from the theoretical-numerical analysis it is evident, that the resistances of compressed cold-formed steel members are significantly influenced by initial imperfections and/or by the initial buckling shapes of their individual webs.

Reached conformity between theoretical calculation according to EN 1993-1-3 and FEM simulation – models without initial imperfections, obtained conformity between experimental results and FEM simulation – taking into account the initial imperfections prove the correctness of ideas and procedures in creating of the calculation models, i.e. these calculation models can be used for further analysis and calculations, see Figure 10.

Previous analysis suggests that the initial imperfections and initial buckling shapes have a serious impact on the resistance of compressed cold-formed members with webs thickness up to 2 mm. At bigger thicknesses the influence of initial imperfections recedes. It has also been found that the intervals between plasticization beginning and failure are markedly higher at bigger thicknesses, see Figure 17.

Large-scale theoretical analysis and experimental research were applied on 18 cold-formed compressed members with different cross-sections of thickness 2 mm. Obtained results from theoretical analysis, experimental tests and numerical simulations of all tested members indicate that the initial buckling shapes and imperfections reduced the resistance of these members and the relevant standard, [1] got to the unguarded side, see Table 3 and Figure 10. This detection raises the question: How to deal with thicknesses up to 2 mm?

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